

Claims

1. A method of designing an intraocular lens capable of reducing aberrations of the eye after its implantation, comprising the steps of:

- 5 (i) characterizing at least one corneal surface as a mathematical model;
- (ii) calculating the resulting aberrations of said corneal surface(s) by employing said mathematical model;
- (iii) selecting the optical power of the intraocular lens;
- 10 (iv) modeling an intraocular lens such that a wavefront arriving from an optical system comprising said lens and corneal model obtains reduced aberrations.

2. A method according to claim 1, comprising determining the resulting aberrations of said corneal surface(s) in a wavefront having passed said cornea.

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3. A method according to claim 1, wherein said corneal surface(s) is(are) characterized in terms of a conoid of rotation.

4. A method according to claim 1 wherein said corneal surface(s) is(are) characterized in terms of polynomials.

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5. A method according to claim 4, wherein said corneal surface(s) is(are) characterized in terms of a linear combination of polynomials.

25 6. A method according to claim 1, wherein said optical system further comprises complementary means for optical correction, such as spectacles or an ophthalmic correction lens.

7. A method according to claim 1, wherein estimations of corneal refractive power and axial eye length designate the selection of lens optical power.

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8. A method according to claim 4, wherein an optical system comprising said corneal model and modeled intraocular lens provides for a wavefront substantially reduced from aberrations as expressed by at least one of said polynomials.

5 9. A method according to claim 1, wherein modeling the intraocular lens includes selecting the anterior radius and surface of the lens, the posterior radius and surface of the lens, lens thickness and refractive index of the lens.

10 10. A method according to claim 9, wherein the aspheric component of the anterior surface is selected while the model lens has predetermined central radii, lens thickness and refractive index.

15 11. A method according to claim 1 including characterizing the front corneal surface of an individual by means of topographical measurements and expressing the corneal aberrations as a combination of polynomials.

20 12. A method according to claim 11 including characterizing front and rear corneal surfaces of an individual by means of topographical measurements and expressing the total corneal aberrations as a combination of polynomials.

13. A method according to claim 1, including characterizing corneal surfaces of a selected population and expressing average corneal aberrations of said population as a combination of polynomials.

25 14. A method according to claim 1, comprising the further steps of :

(v) calculating the aberrations resulting from an optical system comprising said modeled intraocular lens and cornea;

30 (vi) determining if the modeled intraocular lens has provided sufficient reduction in aberrations; and optionally re-modeling the intraocular lens until a sufficient reduction is obtained.

15. A method according to claim 14, wherein said aberrations are expressed as a linear combination of polynomials.
- 5 16. A method according to claim 15, wherein the re-modeling includes modifying one or several of the anterior surface and curvature, the posterior radius and surface, lens thickness and refractive index of the lens.
- 10 17. A method according to claim 4 or 5, wherein said polynomials are Seidel or Zernike polynomials.
18. A method according to claim 17, comprising the steps of:
- (i) expressing the corneal aberrations as a linear combination of Zernike polynomials;
 - 15 (ii) determining the corneal wavefront Zernike coefficients;
 - (iii) modeling the intraocular lens such that an optical system comprising said model lens and cornea provides a wavefront having a sufficient reduction of Zernike coefficients.
- 20 19. A method according to claim 18, further comprising the steps of :
- (iv) calculating the Zernike coefficients of a wavefront resulting from an optical system comprising the modeled intraocular lens and cornea;
 - (v) determining if said intraocular lens has provided a sufficient reduction of Zernike coefficients; and optionally re-modeling said lens until a
 - 25 sufficient reduction is said coefficients are obtained.
20. A method according to claim 19, comprising sufficiently reducing Zernike coefficients referring to spherical aberration.
- 30 21. A method according to claim 19 comprising sufficiently reducing Zernike coefficients referring to aberrations above the fourth order.

22. A method according to claim 20 comprising sufficiently reducing the 11th Zernike coefficient of a wavefront front from an optical system comprising cornea and said modeled intraocular lens, so as to obtain an eye sufficiently free from spherical
5 aberration.

23. A method according to claim 19, wherein the re-modeling includes modifying one or several of the anterior radius and surface, the posterior radius and surface, lens thickness and refractive index of the lens.
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24. A method according to claim 23, comprising modifying the anterior surface of the lens until a sufficient reduction in aberrations is obtained.

25. A method according to claim 17, comprising modeling a lens such that an optical
15 system comprising said model of intraocular lens and cornea provides reduction of spherical and cylindrical aberration terms as expressed in Seidel or Zernike polynomials in a wave front having passed through the system.

26. A method according to claim 25, obtaining a reduction in higher aberration terms.
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27. A method according to claim 8 comprising:

- (i) characterizing corneal surfaces of a selected population and expressing each cornea as a linear combination of polynomials;
 - 25 (ii) comparing polynomial coefficients between individual corneas;
 - (iii) selecting one nominal coefficient value from an individual cornea;
 - (iv) modeling a lens such that a wavefront resulting arriving from an optical system comprising said lens and individual cornea sufficiently reduces said nominal coefficient value.
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28. A method according to claim 27, wherein said polynomial coefficient refers to the Zernike aberration term expressing spherical aberration.

29. A method according to claim 27, wherein said nominal coefficient value is the lowest within the selected population.

30. A method of selecting an intraocular lens that is capable of reducing aberrations of the eye after its implantation comprising the steps of:

- 10 (i) characterizing at least one corneal surface as a mathematical model;
- (ii) calculating the resulting aberrations of said corneal surface(s) by employing said mathematical model;
- (iii) selecting an intraocular lens having a suitable optical power from a plurality of lenses having the same power, but different aberrations;
- 15 (iv) determining if an optical system comprising said selected lens and corneal model sufficiently reduces the aberrations.

31. A method according to claim 30, comprising determining the resulting aberrations of said corneal surface(s) in a wavefront having passed said cornea.

20 32. A method according to claim 30 further comprising the steps of:

- (v) calculating the aberrations of a wave front arriving from an optical system of said selected lens and corneal model;
- (vi) determining if said selected intraocular lens has provided a sufficient reduction in aberrations in a wavefront arriving from said optical system; and optionally repeating steps (iii) and (iv) by selecting at least one new lens having the same optical power until finding a lens capable of sufficiently reducing the aberrations.
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33. A method according to claim 30, wherein said corneal surface(s) is(are) characterized in terms of a conoid of rotation.

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34. A method according to claim 30 wherein said corneal surface(s) is(are) characterized in terms of polynomials.

5 35. A method according to claim 34, wherein said corneal surface(s) is(are) characterized in terms of a linear combination of polynomials.

36. A method according to claim 30 or 32, wherein said optical system further comprises complementary means for optical correction, such as spectacles or an ophthalmic correction lens.

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37. A method according to claim 30, wherein corneal refractive power and axial eye length estimations designate the selection of lens optical power.

15 38. A method according to claim 34 or 35, wherein an optical system comprising said corneal model and selected intraocular lens provides for a wavefront substantially reduced from aberrations as expressed by at least one of said polynomials.

20 39. A method according to claim 30 including characterizing the front corneal surface of an individual by means of topographical measurements and expressing the corneal aberrations as a combination of polynomials.

25 40. A method according to claim 39 including characterizing front and rear corneal surfaces of an individual by means of topographical measurements and expressing the total corneal aberrations as a combination of polynomials.

41. A method according to claim 30, including characterizing corneal surfaces of a selected population and expressing average corneal aberrations of said population as a combination of polynomials.

30 42. A method according to claim 38, wherein said polynomials are Seidel or Zernike polynomials.

43. A method according to claim 42, comprising the steps of:

- 5 (i) expressing the corneal aberrations as a linear combination of Zernike polynomials;
- (ii) determining the corneal Zernike coefficients;
- (iii) selecting the intraocular lens such that an optical system comprising said lens and cornea provides a wavefront having a sufficient reduction in Zernike coefficients.

10 44. A method according to claim 43, further comprising the steps of :

- (iv) calculating the Zernike coefficients resulting from an optical system comprising the modeled intraocular lens and cornea;
- 15 (v) determining if said intraocular lens has provided a reduction of Zernike coefficients; and optionally selecting a new lens until a sufficient reduction in said coefficients is obtained.

45. A method according to claim 43 or 44, comprising determining Zernike polynomials up to the 4th order.

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46. A method according to claim 45 comprising sufficiently reducing Zernike coefficients referring to spherical aberration.

25 47. A method according to claim 46 comprising sufficiently reducing Zernike coefficients above the fourth order.

48. A method according to claim 46 comprising sufficiently reducing the 11th Zernike coefficient of a wavefront front from an optical system comprising model cornea and said selected intraocular lens, so as to obtain an eye sufficiently free from spherical aberration.

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49. A method according to claim 39 comprising selecting an intraocular lens such that an optical system comprising said intraocular lens and cornea provides reduction of spherical aberration terms as expressed in Seidel or Zernike polynomials in a wave front having passed through the system.

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50. A method according to claim 39, wherein reduction in higher aberration terms is accomplished.

51. A method according to claim 30 characterized by selecting an intraocular lens from a kit comprising lenses with a suitable power range and within each power range a plurality of lenses having different aberrations.

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52. A method according to claim 51, wherein said aberrations are spherical aberrations.

53. A method according to claim 51, wherein said lenses within each power range have surfaces with different aspheric components.

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54. A method according to claim 53, wherein said surfaces are the anterior surfaces.

55. A method of designing an ophthalmic lens suitable for implantation into the eye, characterized by the steps of:

- selecting a representative group of patients;
- collecting corneal topographic data for each subject in the group;
- transferring said data to terms representing the corneal surface shape of each subject for a preset aperture size;
- calculating a mean value of at least one corneal surface shape term of said group, so as to obtain at least one mean corneal surface shape term and/or calculating a mean value of at least one to the cornea corresponding corneal wavefront aberration term, each corneal wavefront aberration term being obtained by transformation through corneal surface shape terms;

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- from said at least one mean corneal surface shape term or from said at least one mean corneal wavefront aberration term designing an ophthalmic lens capable of reducing said at least one mean wavefront aberration term of the optical system comprising cornea and lens.

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56. Method according to claim 55, characterized in that it further comprises the steps of:

- designing an average corneal model for the group of people from the calculated at least one mean corneal surface shape term or from the at least one mean corneal wavefront aberration term;
- 10 - checking that the designed ophthalmic lens compensates correctly for the at least one mean aberration term by measuring these specific aberration terms of a wavefront having traveled through the model average cornea and the lens and redesigning the lens if said at least one aberration term not has been sufficiently reduced in the measured wavefront.

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57. Method according to claim 55 or 56, characterized by calculating surface descriptive constant for the lens to be designed from the mean corneal surface shape terms or from the mean corneal wavefront aberration terms for a predetermined radius.

- 20 58. Method according to any one of the claims 55-57, characterized by selecting people in a specific age interval to constitute the group of people.

59. Method according to any one of the claims 55-58, characterized by selecting people who will undergo cataract surgery to constitute the group of people.

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60. Method according to any one of the claims 55-59, characterized by designing the lens specifically for a patient that has undergone corneal surgery and therefor selecting people who have undergone corneal surgery to constitute the group of people.

- 30 61. Method according to any one of the claims 55-60, characterized by selecting people who have a specific ocular disease to constitute the group of people.

62. Method according to any one of the claims 55-61, characterized by selecting people who have a specific ocular optical defect to constitute the group of people.

5 63. Method according to any one of the claims 55-62, characterized in that it further comprises the steps of:

- measuring the at least one wavefront aberration term of one specific patient's cornea;
- determining if the selected group corresponding to this patient is representative for this specific patient and if this is the case implant the lens designed from these
- 10 average values and if this not is the case implant a lens designed from average values from another group or design an individual lens for this patient.

64. Method according to any one of the claims 55-63, characterized by providing the lens with at least one nonspheric surface that reduces at least one aberration term of an

15 incoming nonspheric wavefront.

65. Method according to claim 64, characterized in that said aberration term is a positive spherical aberration term.

20 66. Method according to any one of the claims 55-65, characterized by providing the lens with at least one nonspheric surface that reduces at least one term of a Zernike polynomial representing the aberration of an incoming nonspheric wavefront.

67. Method according to claim 66, characterized by providing the lens with at least one

25 nonspheric surface that reduces the 11th normalized Zernike term representing the spherical aberration of an incoming nonspheric wavefront.

68. A method according to any of claims 55-67 characterized by designing a lens to reduce spherical aberration in a wavefront arriving from an average corneal surface

having the formula:
$$z = \frac{(\frac{1}{R})r^2}{1 + \sqrt{1 - (\frac{1}{R})^2(cc + 1)r^2}} + adr^4 + aer^6$$

wherein the conical constant cc has a value ranging between -1 and 0, R is the central lens radius and ad and ae are aspheric constants.

69. A method according to claim 68, wherein the conical constant (cc) ranges from about -0.05 for an aperture size (pupillary diameter) of 4 mm to about -0.18 for an aperture size of 7 mm.

70. Method according to claim 68, characterized by providing the lens with a surface described by a modified conoid having a conical constant (cc) less than 0.

71. Method according to any one of the claims 55-70, characterized by providing the lens with a, for the patient, suitable refractive power, this determining the radius of the lens.

72. Method according to any one of the claims 55-71, characterized by designing the lens to balance the spherical aberration of a cornea that has a Zernike polynomial coefficient representing spherical aberration of the wavefront aberration with a value in the interval from 0.000156 mm to 0.001948 mm for a 3 mm aperture radius using polynomials expressed in OSLO format.

73. Method according to any one of the claims 55-71, characterized by designing the lens to balance the spherical aberration of a cornea that has a Zernike polynomial coefficient representing spherical aberration of the wavefront aberration with a value in the interval from 0.000036 mm to 0.000448 mm for a 2 mm aperture radius using polynomials expressed in OSLO format.

74. Method according to any one of the claims 55-71, characterized by designing the lens to balance the spherical aberration of a cornea that has a Zernike polynomial coefficient representing spherical aberration of the wavefront aberration with a value in the interval from 0.0001039 mm to 0.0009359 mm for a 2,5 mm aperture radius using polynomials expressed in OSLO format.

75. Method according to any one of the claims 55-71, characterized by designing the lens to balance the spherical aberration of a cornea that has a Zernike polynomial coefficient representing spherical aberration of the wavefront aberration with a value in the interval from 0.000194 mm to 0.00365 mm for a 3,5 mm aperture radius using polynomials expressed in OSLO format.

76 An ophthalmic lens obtained in accordance with any of claims 1 to 75, capable of transferring a wavefront having passed through the cornea of the eye into a substantially spherical wavefront having its center in the retina of the eye.

77. An ophthalmic lens capable of compensating for the aberrations of a corneal model designed from a suitable population, such that a wavefront arriving from an optical system comprising said model cornea and said lens obtains substantially reduced aberrations.

78. An ophthalmic lens according to claim 77, wherein said corneal model includes average aberration terms calculated from characterizing individual corneas and expressing them in mathematical terms so as to obtain individual aberration terms..

79. An ophthalmic lens according to claim 77, wherein said aberration terms is a linear combination of Zernike polynomials.

80. An ophthalmic lens according to claim 79 capable of reducing aberration terms expressed in Zernike polynomials of said corneal model, such that a wavefront arriving

from an optical system comprising said model cornea and said lens obtains substantially reduced spherical aberration.

5 81. An ophthalmic lens according to claim 80 capable of reducing the 11th Zernike term of the 4th order.

82. An ophthalmic lens according to claim 77 being an intraocular lens.

10 83. An ophthalmic lens according to claim 77 adapted to replace the natural lens in a patient's eye, said ophthalmic lens having at least one nonspheric surface, this at least one nonspheric surface being designed such that the lens, in the context of the eye, provides to a passing wavefront at least one wavefront aberration term having substantially the same value but with opposite sign to a mean value of the same aberration term obtained from corneal measurements of a selected group of people, to which said patient is
15 categorized, such that a wavefront arriving from the cornea of the patient's eye obtains a reduction in said at least one aberration term provided by the cornea after passing said lens.

20 84. An ophthalmic lens according to claim 83, characterized in that the surface of the lens is designed to reduce at least one positive aberration term of a passing wavefront.

25 85 An ophthalmic lens according to claim 83 or 84, characterized in that the at least one wavefront aberration term provided to the passing wavefront by the lens is a spherical aberration term, such that a wavefront arriving from the cornea of the patient's eye obtains a reduction in said spherical aberration term provided by the cornea after passing said lens.

30 86. An ophthalmic lens according to any one of the claims 83-85, characterized in that the at least one wavefront aberration term provided to the passing wavefront by the lens is at least one term of a Zernike polynomial representing the wavefront aberration of the cornea.

87. An ophthalmic lens according to claim 86, characterized in that the at least one wavefront aberration term provided to the passing wavefront by the lens is the 11th normalized Zernike term of a wavefront aberration of the cornea.

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88. An ophthalmic lens according to any one of the claims 83-87, characterized in that said selected group of people is a group of people belonging to a specific age interval.

89. An ophthalmic lens according to any one of the claims 83-88, characterized in that the lens is adapted to be used by a patient that has undergone corneal surgery and in that said selected group of people is a group of people who have undergone corneal surgery.

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90. An ophthalmic lens according to any one of the claims 83-88, characterized in that said selected group of people is a group of people who will undergo a cataract surgical operation.

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91. An ophthalmic lens according to claim 90 characterized in that the nonspheric surface is a modified conoid surface having a conical constant (cc) less than zero.

92. An ophthalmic lens according to claim 91 characterized in that that is capable of eliminating or substantially reducing spherical aberration of a wavefront in the eye or in an eye model arriving from a prolate surface having the formula:

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$$z = \frac{(\frac{1}{R})r^2}{1 + \sqrt{1 - (\frac{1}{R})^2(\mathbf{cc} + 1)r^2}} + \mathbf{ad}r^4 + \mathbf{ae}r^6$$

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the conical constant cc has a value ranging between -1 and 0, R is the central lens radius and ad and ae are aspheric constants.

93. An ophthalmic lens according to any one of the claims 83-92, characterized in that the lens is provided with a, for the patient, suitable refractive power less than or equal to 30 diopters.

94. An ophthalmic lens according to any one of the claims 83-93, characterized in that one of the at least one nonspheric surface of the lens is the anterior surface.

5 95. An ophthalmic lens according to any one of the claims 83-94, characterized in that one of the at least one nonspheric surface of the lens is the posterior surface.

96. An ophthalmic lens according to any one of the claims 83-95, characterized in that the lens is made from a soft biocompatible material.

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97. An ophthalmic lens according to any one of the claims 83-96, characterized in that the lens is made of a silicone material.

98. An ophthalmic lens according to claim 97, characterized in that the silicone material
15 is characterized by a refractive index larger than or equal to 1.43 at a wavelength of 546 nm, an elongation of at least 350 %, a tensile strength of at least 300 psi and a shore hardness of about 30 as measured with a Shore Type A Durometer.

99. An ophthalmic lens according to any one of the claims 83-98, characterized in that the
20 lens is made of hydrogel.

100. An ophthalmic lens according to any one of the claims 83-95, characterized in that the lens is made of a rigid biocompatible material.

25 101. An ophthalmic lens according to any one of the claims 83-100, characterized in that it is designed to balance the spherical aberration of a cornea that has a Zernike polynomial coefficient representing spherical aberration of the wavefront aberration with a value in the interval from 0.000156 mm to 0.001948 mm for a 3 mm aperture radius using polynomials expressed in OSLO format.

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102. An ophthalmic lens according to any one of the claims 83-100, characterized in that it is designed to balance the spherical aberration of a cornea that has a Zernike polynomial coefficient representing spherical aberration of the wavefront aberration with a value in the interval from 0.000036 mm to 0.000448 mm for a 2 mm aperture radius
5 using polynomials expressed in OSLO format.

103. An ophthalmic lens according to any one of the claims 83-100, characterized in that it is designed to balance the spherical aberration of a cornea that has a Zernike polynomial coefficient representing spherical aberration of the wavefront aberration with
10 a value in the interval from 0.0001039 mm to 0.0009359 mm for a 2.5 mm aperture radius using polynomials expressed in OSLO format.

104. An ophthalmic lens according to any one of the claims 83-100, characterized in that it is designed to balance the spherical aberration of a cornea that has a Zernike
15 polynomial coefficient representing spherical aberration of the wavefront aberration with a value in the interval from 0.000194 mm to 0.00365 mm for a 3.5 mm aperture radius using polynomials expressed in OSLO format.

105. An ophthalmic lens having at least one nonspherical surface which when expressed
20 as a linear combination of polynomial terms representing its aberrations is capable of reducing similar such aberration terms obtained in a wavefront having passed the cornea, thereby obtaining an eye sufficiently free from aberrations.

106. A lens according to claim 105, wherein said nonspherical surface is the anterior
25 surface of the lens.

107. A lens according to claim 106, wherein said nonspherical surface is the posterior surface of the lens.

30 108. A lens according to claim 105, being an intraocular lens.

109. A lens according to claim 105, wherein said polynomial terms are Zernike polynomials.

110. A lens according to claim 109 capable of reducing polynomial terms representing
5 spherical aberrations and astigmatism.

111. A lens according to claim 110, capable of reducing the 11th Zernike polynomial term of the 4th order.

10 112. A lens according to claim 105 made from a soft biocompatible material.

113. A lens according to claim 105 made of silicone.

114. A lens according to claim 105 made of hydrogel.

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115. A lens according to claim 105 made of a rigid biocompatible material.

116. A method of performing visual correction in a patient by implanting an intraocular lens, which at least partly compensates for the aberrations of the eye, comprising the

20 steps of:

- removing the natural lens from the eye;
- measuring the aberrations of the eye not comprising the lens by using a wavefront sensor;
- providing a lens that is capable reducing at least one aberration term as found by the
25 wavefront sensing;
- implanting the lens into the eye of the patient.

117. A method according to claim 116, wherein the lens is provided by selection from a kit of lenses which includes a plurality of lenses with different capacity to correct said at
30 least one aberration term within each diopter..

118. A method according to claim 116, wherein the lens is provided by designing a lens that is capable of reducing at least one aberration term resulting from the wavefront sensing of the aphakic eye.

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